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Geothermal Properties of Northern Iran (Southern Caspian Sea coasts): A Comparative Geological and Hydrogeochemical Analysis

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ABSTRACT

Southern Caspian Sea region is located in north of Iran. Gilan, Mazandaran and Golestan are three Provinces in this region. Geothermal activities in this area are directly related to tectonics and significant heat-generating rocks. The active tectonic zone of the Alborz Mountains along the southern coast of the Caspian Sea contains a diverse array of thermal springs. This paper presents a comparative analysis of the major geothermal systems in this region, integrating geological, tectonic, and hydrogeochemical data from four key areas: Gilan, Ramsar (in Mazandaran Province), Damavand (in Mazandaran Province), and Golestan. It is identified and characterized three distinct geothermal types: 1) Volcanic system (Damavand), defined by a magmatic heat source, mixed-anion chemistry, and high-enthalpy potential (T: ~150–280°C); 2) Tectonic system (Gilan and Golestan) characterized by fault-driven shallow circulation, immature Ca-Mg-HCO_3 waters, and low-enthalpy (T <45°C); and 3) Radiogenic system (Ramsar) that is distinguished by deep fault circulation, mature Na-Cl waters influenced by Caspian Sea intrusion, and high natural radiogenic from ^{226}Ra and ^{222}Rn. This regional synthesis highlights how variations in underlying heat source, fluid circulations, and host rock geology control the geochemical specification, resource potential, and environmental implications of geothermal manifestations across northern Iran.

1 INTRODUCTION

Research on geothermal resources, which play a significant role in renewable energy today, has gained momentum. Many countries use this resource for both energy production and direct applications. Significant investments have been made in countries such as Türkiye and China (Baba and Chandrasekharam,2022; Chandrasekharam and Baba, 2022). Although many studies have examined the Southern Caspian Sea from geological and tectonic perspectives, very few have addressed it from a geothermal perspective (Berberian and Berberian, 1981; Berberian, 1983; Priestley et al., 1994; Jackson et al., 2002; Allen et al., 2003; Farhoudi and Mohebbi, 1989; Mosadeghzadeh et al., 2019; Guest et al.,2007). The northern margin of Iran, along the southern coast of the Caspian Sea, is a region of significant geothermal activity. This activity directly reflects the complex tectonic interaction between the Arabian and Eurasian plates, with the South Caspian Basin serving as a rigid, subsiding backstop (Figure 1) (Guest et al., 2006a; Vernant et al., 2004). The Alborz Mountain range, a major orogenic belt formed by this collision, provides the structural framework for the circulation and discharge of thermal fluids (Alizadeh Saloomahalleh and Eshaghpour, 2009).

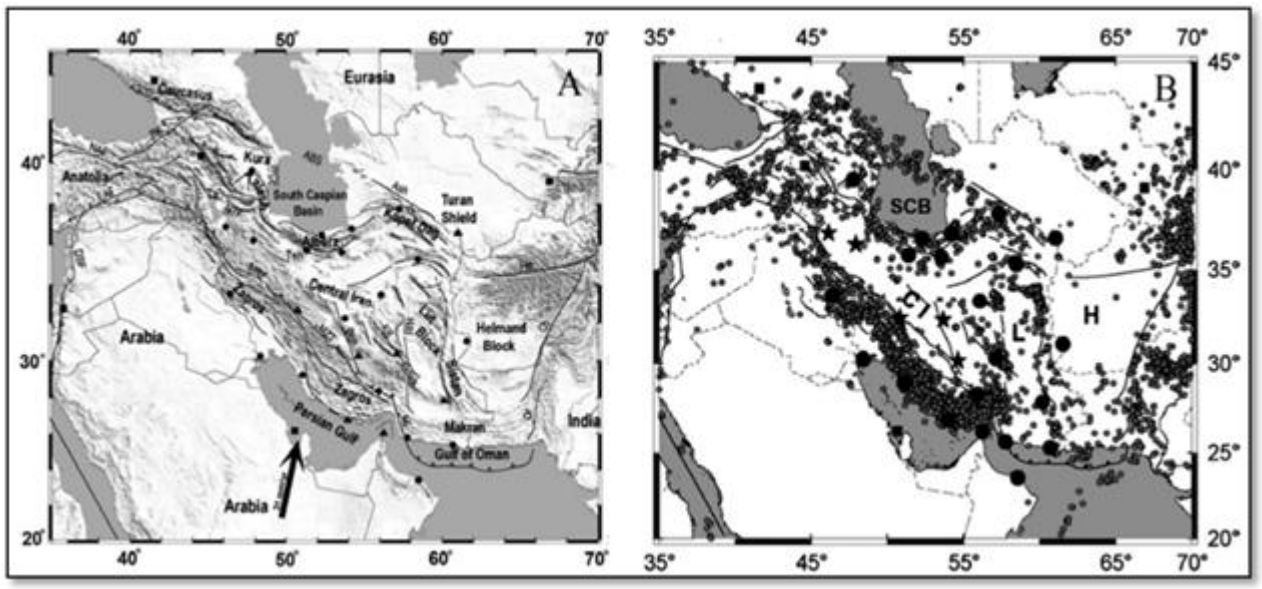


Figure 1. Tectonics of the study area: Alborz highlands in north of Iran and South Caspian Block (SCB). Kopah Dagh highlands in the east and Talesh in the west. Central Iran, (L), Caucasus and Zagros mountain ranges also obvious. The small hollow dots represent earthquakes that occur in the areas (Farhoudi and Mohebbi, 2010).

Although thermal springs are widespread along the Alborz mountains, their characteristics, types and systems are different. Previous studies have often focused on individual, prominent sites, such as the radiogenic springs of Ramsar or the volcanic system of Damavand. However, a systematic regional comparison reveals a range of geothermal systems controlled by distinct geological mechanisms. This paper synthesizes data from 3 key provinces: Gilan, Mazandaran(with a focus on Ramsar and Damavand) and Golestan to present an integrated geological and hydrogeochemical analysis.

The objectives of this study are to: a) delineate the primary geothermal types (volcanic, tectonic, radiogenic) present in the region; b) clarify the links between tectonic setting, heat source, and resulting hydrogeochemical signatures; c) compare the geothermal potential and environmental implications, including the unique radiological hazard in Ramsar; and d) provide a framework for region-specific sustainable management of these resources.

2 GEOLOGICAL AND TECTONIC SETTING

The Alborz Mountains form a seismically active, doubly vergent fold-and-thrust belt. The overall tectonic regime is dominated by oblique shortening, accommodated by major strike-slip and reverse faults, most notably the North Alborz Fault System (NAFS), which parallels the Caspian coastline (Eshaghpour and Alizadeh Saloomahalleh, 2015). The contrasting crustal properties between the Central Iran that actually is a plateu and the submerged, oceanic-like crust of the South Caspian Basin create a steep gradient that strongly influences fluid flow and heat distribution.

Ramsar and Gilan: Situated in the western Alborz, these areas are influenced by the interaction between the Alborz range and the South Caspian Basin. Ramsar's springs are directly controlled by the deep-reaching NAFS, while Gilan's springs are associated with more distributed neotectonic faulting and uplift (Eshaghpour et al., 2010). The geothermal systems in this area are summarized below (Figure 2 and Figure 3).

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Damavand: Located in the central Alborz, this area is dominated by the Quaternary stratovolcano Mount Damavand, which provides a potent magmatic heat source. The system is fault-controlled, but the driving force is the shallow magmatic intrusion (Nouraliee et al., 2010).

Golestan: In the eastern Alborz, the tectonic setting transitions toward the Kopeh Dagh range. Thermal springs here, such as the Ziarat spring near Gorgan, are typically controlled by thrust faults and are associated with the deep circulation of meteoric water in the absence of recent volcanism (Raghimi and Yakhkeshi, 2002).

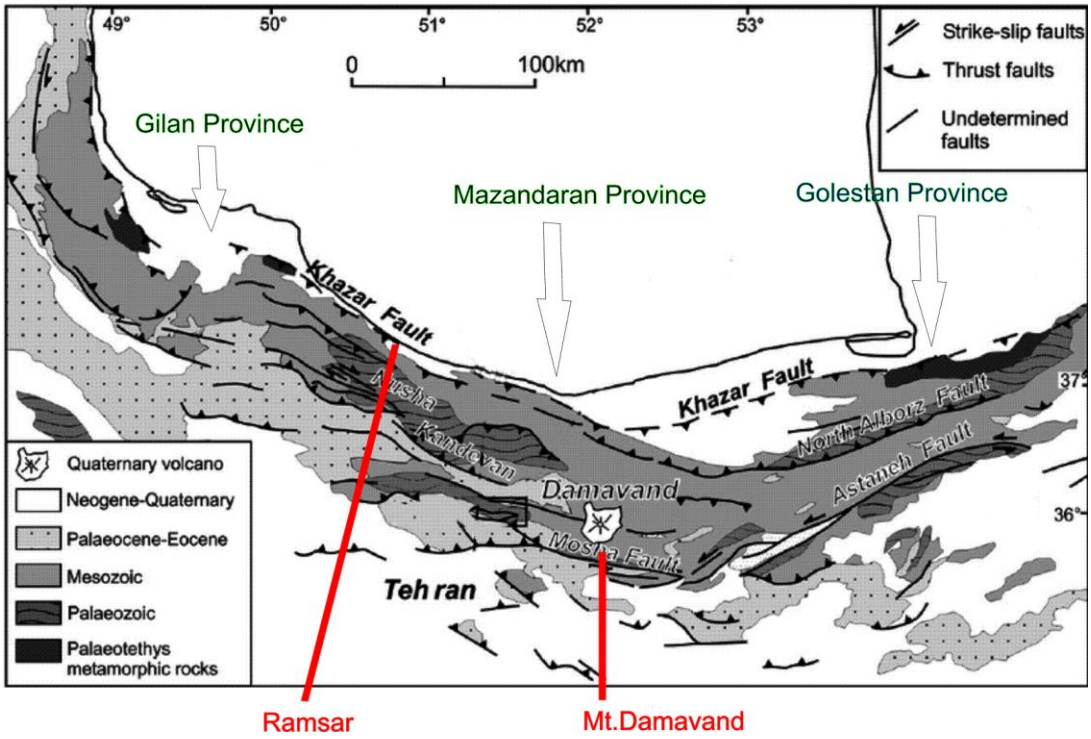


Figure 2. Alborz highlands, Gilan in the west, Mazandaran with Damavand summit in the center and Golestan in the east (modified from Guest et al., 2007).

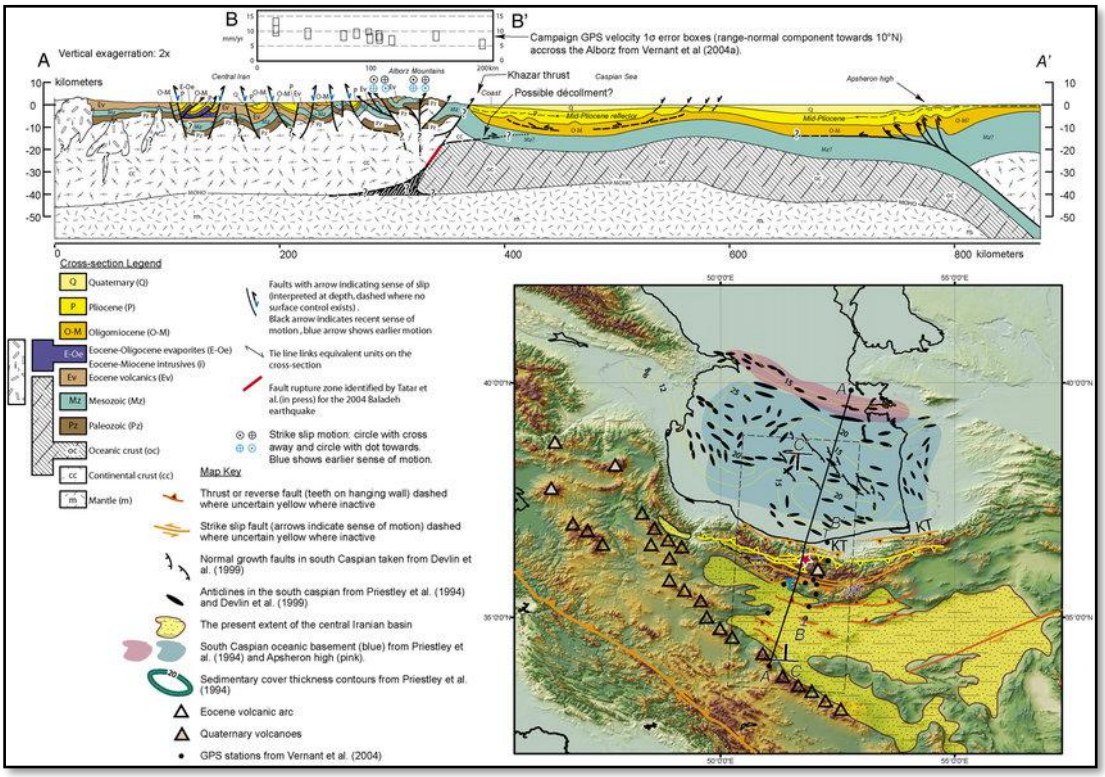


Figure 3. Tectonic map and cross-section showing the basic tectonic setting of northern Iran and the South Caspian Basin (Guest et al., 2006a,b, 2007).

3 HYDROGEOCHEMISTRY OF REGION

The hydrogeochemical composition of the thermal springs provides critical insights into their origin, circulation depth, and heat source. The distinct signatures of the four study areas are summarized in Table 1. Figure 2 also presents the geological and tectonic features of these geothermal fields in a simplified manner. Figure 3 clearly illustrates the relationship between tectonics and magmatic rocks in the geological section. Viewed holistically, the area exhibits a heterogeneous hydrogeochemical structure, with significant variations in temperature and water chemistry. This variation is entirely related to the geological characteristics of the area, and water-rock interaction is active. In the Gilan Province, the fluid generally has a low temperature, while in the Ramsar region, temperatures range from 20 to 280°C. Hot water sources in the Ramsar region are deep-circulating, and the area is rich in radionuclides. This highlights the importance of the geothermal field. The Damavand Region has mixed water types, with geothermal fluid temperatures ranging from 80 to 150°C, and higher gas concentrations in the area. In Golestan Province, located in the far east of the region, water resources are also deep-circulating, with temperatures ranging from 40 to 150°C.

3.1 Gilan and Golestan Geothermal System

These systems are characterized by shallow to intermediate circulation driven by tectonic heat. Gilan springs exhibit an immature Ca-Mg-HCO_3 signature, indicating short water-rock interaction times with carbonate rocks (Eshaghpour et al., 2010). Their reservoir temperatures are consistently lower than those of volcanic systems, making them suitable for direct-use applications such as balneology. The hot springs in Gilan Province can be categorized into three different geographical areas: Southern Gilan, Western Gilan, and Eastern Gilan. These springs are located in highlands with a minimum elevation of 165 m above sea level. Hot springs flow

lithologically in hard rock formations. It should be noted that the coastal plain has an elevation below sea level. In the southern part of Gilan Province, around Rudbar city, there are three hot springs: Luye, Sangrood, and Aliabad. The first two was sampled by the Regional Water Company of Gilan twice each year, in september and march, indicating no significant difference between dry and wet seasons. Sangrood hot spring is located near Sangrood village. The old morphology of the spring consisted of travertine terraces, which were mostly destroyed by mining and road construction over the past decades (Eshaghpour et al. (2010). Sangrood spring is located about 5 km from the Sangrood coal mine and still is a place for bathing and baleonological direct use utilization. Precipitation infiltrates the Ruteh Formation limestones, moves downward along a local fault, comes into contact with Paleogene volcanic rock, heats up, and then rises to the surface. The surface temperature is about 32°C. CO_2 bubbles are visible in all of the springs. According to local people, several decades ago, the spring's discharge was much higher than it is now. The current discharge of the spring is about 2 l/s.

In Golestan, thermal springs such as Ziarat display a more evolved Na-Cl or Na-HCO_3 type, suggesting a deeper circulation path and longer residence time, possibly interacting with evaporate layers or undergoing cation exchange, but still in a non-magmatic context (Raghimi and Yakhkeshi, 2002). Golestan also is home to 3 active mud volcanoes: Naftliche, Gharniyaragh and Incheborun. 98% of the gases of these mud volcanoes is methane. An upcoming diaper is found near Gharniyarigh mud volcano. According to these data and active tectonic of southern Caspian Sea these mud volcanoes are categorized as tectonic-sedimentary mud volcanoes (Faslbahar et al, 2009).

Gilan and Golestan are ideal for balneology and health tourism. Their safer, lower-temperature springs can be developed into wellness resorts, leveraging the region's natural beauty where the unique Hyrcanian forests that are covered from sea level up to an altitude of 2,800 m and comprise 1.1% of the country"s area (Sagheb Talebi et al., 2014).

Table 1. Hydrogeochemical properties of Gilan Province (1: South of Gilan, 2: West of Gilan, 3: East of Gilan (Eshaghpour et al, 2010).

	Area	Name	X	Y	Z	Geology	Q (l/s)	Utilization	T (°C)	EC	pH
2	Lavandevil	Kuta'Kuma' 1	306080	4242104	165	Cretaceous Shale and Sandstone layers	0.40	Baleonology	36	752	9.1
	Lavandevil	Kuta'Kuma' 2	306093	4242242	234	Cretaceous Shale and Sandstone layers	0.05	Drinking	33	254	8.0
	Lavandevil	Kuta'Kuma' 3	306017	4242955	394	Cretaceous Shale and Sandstone layers	0.10	Cow farming	33	207	8.0
	Astara- Chamlar	Alidashi	292812	4245994	667	strongly tectonicized paleogene Andesite	3.50	no	32	263	9.3
	Astara- Chamlar	Abgarm	292824	4245897	680	Paleogene Andesite	1.00	no	31	258	9.3
	Astara	Gildeh	296149	4250474	839	Paleogene Sandstone and shale	0.02	Cow farming	30	127	8.3
	Date of Sampling: July & August 2009, EC: micro S/cm										
3	Rahimabad	Garmabdasht	430919	4080596	458	Jurasic Karstic limstone	2.00	no	21	1092	6.8
2: Eastern Gilan Date of sampling: August 2009											

3.2 The Volcanic System: Damavand

Mt.Damavand (5610 masl) is the highest volcano in all Asia and is one of the iconic symbols of Iran. Its peak is located in Mazandaran province but the mountain slopes are divided by two provinces of Mazandaran in the north and Tehran in the south. The Damavand region is the leading high-enthalpy prospect in northern Iran. The springs exhibit mixed anion chemistry (Cl-SO_4-HCO_3), characteristic of volcanic-related systems influenced by magmatic gases and high-temperature water-rock interaction (Nouraliee et al., 2010). Geothermometers such as Na-K-Ca predict deep reservoir temperatures ranging from 150°C to over 280°C, confirming a significant magmatic heat source. The reservoir is hosted in Triassic-Paleozoic carbonates and sealed by the thick Shemshak Formation, forming a classic confined geothermal system with potential for electricity (power) generation.

3.3 The Radiogenic System: Ramsar

Ramsar remains a global anomaly. Its mature Na-Cl waters, with extremely high salinity, result from deep circulation and extensive water-rock interaction. The salinity is attributed to the intrusion and thermochemical alteration of Caspian Sea water along the NAFS (Samadi, 2013). The weakly acidic nature of these fluids facilitates the leaching of radium-226 (^{226}Ra) from deep, uranium-rich Tertiary plutons (Rezaei et al., 2021). This process produces the unique radiogenic character that defines this system, with severe environmental consequences.

Ramsar is a globally recognized site for High Natural Background Radiation (HNBR). The transport of ^{226}Ra and its decay product ^{222}Rn to the surface has resulted in soil activities up to 3,700 Bq/kg and indoor radon concentrations exceeding 10,000 Bq/m^3 (Sohrabi, 2013). This presents a complex medical geology paradox: although radon is a known lung carcinogen, long-term epidemiological studies of Ramsar's residents have not demonstrated a clear increase in cancer mortality, fueling the debate on radiation hormesis (Mortazavi et al., 2005, 2017). Prudent public health policy requires continuous monitoring and remediation efforts, such as implementing building ventilation standards.

Table 2. Comparative summary of the thermal spring systems in north of Iran.

Feature	Gilan Province	Ramsar Area (Mazandaran Province)	Damavand Region (Mazandaran Province)	Golestan Province
Primary Control	Tectonic/Neotectonics (Shallow)	Fault-Controlled, Radiogenic (Deep)	Volcanic/Magmatic (Deep)	Tectonic/Thrust Faults (Intermediate)
Dominant Water Type	Ca-Mg-HCO_3	Na-Cl	Cl-SO_4-HCO_3 (Na-Ca)	Na-Cl to Na-HCO_3
Surface Temp.	Max ~36°C (Eshaghpour et al., 2010)	20 - 50°C (Samadi, 2013)	Wide range, up to ~85°C (Nouraliee et al., 2010)	Moderate (e.g., Ziarat: ~40°C) (Raghimi and Yakhkeshi, 2002)
Reservoir Temp. (Est.)	Low (Ambient to low-grade)	90 to 280°C (Samadi, 2013)	80 to 150 °C (Nouraliee et al., 2010)	Moderate (~100-150°C)
Salinity (EC µS/cm)	Lower	From 1050 to 21,600) (Samadi, 2013)	Variable, often high	High (e.g., Ziarat: ~7000) (Raghimi and Yakhkeshi, 2002)
Key Characteristic	Shallow groundwater influence	Extreme radiogenic activity (^{226}Ra,^{22}Rn) (Sohrabi, 2013)	High-Enthalpy, Volcanic Gas Influence	Mixing of deep saline & meteoric waters

4 RESULT AND CONCLUSION

The Caspian Sea is a geologically mysterious creature. Its oceanic crust and depression hosted great hydrocarbon reservoirs. Meanwhile in southern parts in northern Iran, it is sitting on a vast, mostly untapped geothermal treasure toward highlands. Each region offers a different kind of opportunity. Based on the geological and hydrogeochemical data obtained, the area is considered to have high geothermal potential. However, the use of geothermal resources in this area remains limited. Currently, there are small-scale health tourism activities in the area. The Damavand region holds the highest potential for geothermal power generation in northern Iran, with estimates suggesting a potential of 70–100 MWe. The primary challenge is confirming reservoir properties through deep exploratory drilling (Nouraliee et al., 2010). Gilan and Golestan provinces are ideally suited for balneological and recreational tourism. Their lower-temperature, low-risk springs can be developed for health and wellness tourism, capitalizing on the natural scenery of the Alborz forests and Caspian coastline (Eshaghpour et al., 2010). The Ramsar region offers balneology but is complicated by the radiological

context. Its well-developed infrastructure supports tourism, but sustainable development must integrate radiation safety measures for visitors and workers.

In summary, this regional comparative analysis shows that the thermal springs of northern Iran can be classified into three distinct genetic types, each with unique characteristics:

Volcanic Systems (Damavand): Driven by shallow magmatic intrusions, these high-enthalpy systems have mixed-anion chemistry and the highest potential for electricity generation. Damavand holds the most promise for generating clean electricity, potentially enough to power tens of thousands of homes. The next step is deep exploratory drilling to confirm the reservoir's potential.

Tectonic Systems (Gilan and Golestan Provinces): Driven by fault-controlled circulation of meteoric water, these low- to moderate-enthalpy systems range from immature (Gilan) to more evolved (Golestan) geochemistry and are best suited for direct heat use and balneological tourism.

Radiogenic System (Ramsar): A subset of tectonic systems where deep fluid circulation through uranium-rich basement rocks produces a mature Na-Cl water type and extreme natural radiogenic activity, presenting unique environmental health challenges. Ramsar also has tourism potential, but it requires a careful and specialized approach that balances development with rigorous radiation safety for both visitors and workers.

This typology provides a robust framework for strategic resource management. Future efforts in Damavand should focus on exploratory drilling for power development. Its close distance (66 km away) to capital of Iran with populations about 18 million people, is a great opportunity. In Gilan and Golestan, the emphasis should be on sustainable tourism development. For Ramsar, an approach for balancing tourism with rigorous radiological protection and ongoing health research is helpful. Understanding these geological distinctions is key to unlocking the diverse potential of Iran's Caspian geothermal resources.

For the specified regions, detailed geothermal studies should be conducted first. Further strategic plannings should be provided for these activities, and it is extremely important to carry out drilling for production and reinjection purposes in the area. Conducting these studies will enable the discovery of high geothermal potential. These applications will be important not only for the region's economy but also for the country's economy. Thus, fossil fuel consumption will be reduced and CO2 levels will be lowered. Ramsar also has tourism potential, but it requires a careful and specialized approach that balances development with rigorous radiation safety for both visitors and workers. In short, the geothermal landscape of Northern Iran is not a homigenic. It's a diverse tapestry woven by fire, water, and rock. By appreciating the unique character of each system: the volcanic, the tectonic, and the radiogenic, we can develop a smart, sustainable strategy to harness this clean energy.

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